

National Aeronautics and Space Administration



Update on the NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization (2015, 2016)

Judith Van Zante, Timothy Bencic, Thomas Ratvasky

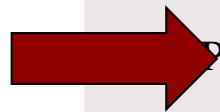
Presented by: Judy Van Zante

NASA Glenn Research Center

2016 AIAA Aviation, Jun 13 - 17, 2016, Washington, D. C.

PSL Icing Session

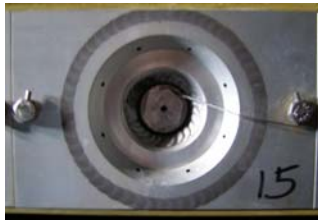
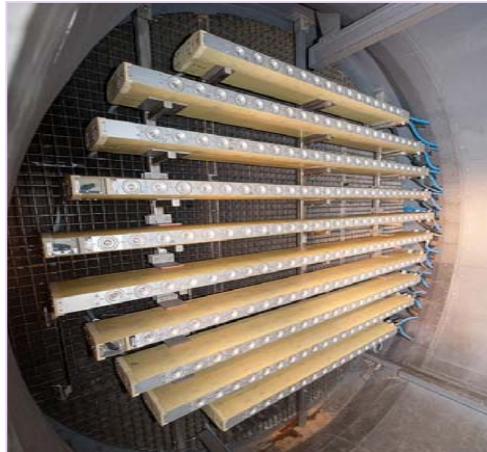
Time	Topic	Presenter
2:00 PM	Turbofan Ice Crystal Rollback Investigation and Preparations Leading to the Second, Heavily Instrumented, Ice Crystal Engine Test at NASA PSL-3 Test Facility	R. Goodwin
2:30 PM	Determination of engine recovery after an ice accretion rollback, engine performance deterioration and health monitoring using minimal instrumentation during icing testing at NASA Glenn PSL-3	D. Walker
3:00 PM	Preliminary Results from a Heavily Instrumented Engine Ice Crystal Icing Test in a Ground Based Altitude Test Facility	A. Flegel
3:30 PM	Modeling of Highly Instrumented Honeywell Turbofan Engine Tested with Ice Crystal Ingestion in the NASA PSL	J. Veres
4:00 PM	Test Point Selection for Engine Crystal Icing Test at NASA PSL-3 for focused sensitivity, peak intensity, and anti-ice evaluations	D. Dischinger
4:30 PM	NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization Update (2015)	J. Van Zante
5:00 PM	Aircraft engine icing instrumentation used in the NASA Glenn Propulsion Systems Laboratory	T. Bencic



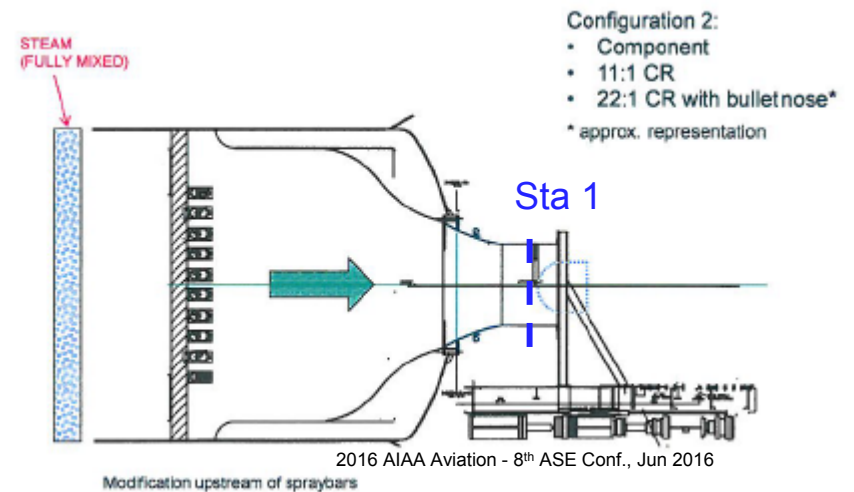
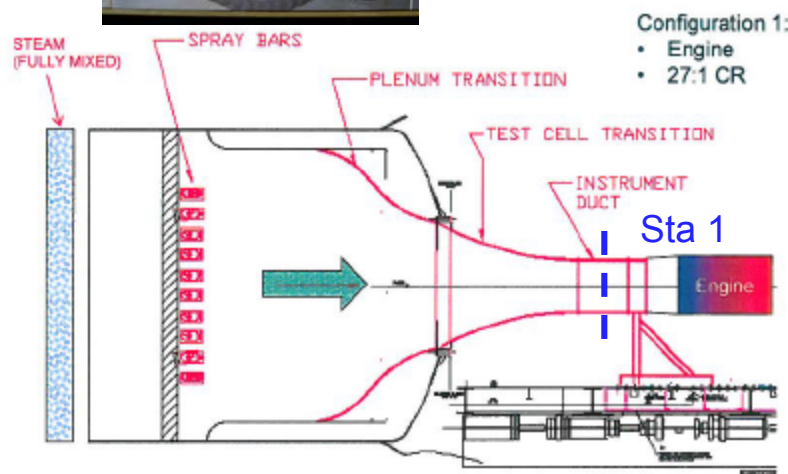
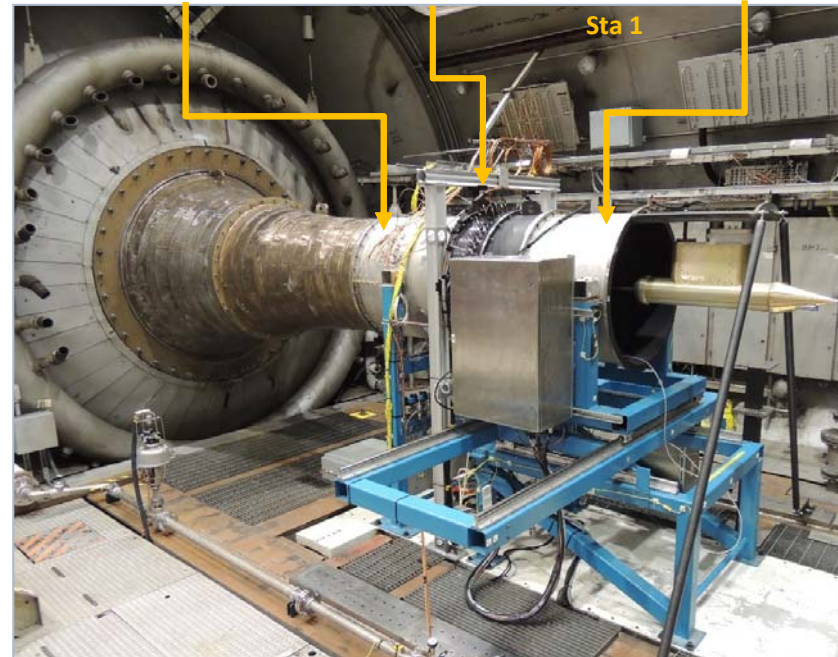
Outline

- Facility Description
- Cloud Characterization Parameter Space
- Aspects Characterized
- Conclusions

PSL Facility



Aero-Thermal Duct Tomography & Raman Cloud Calibration Duct



2016 AIAA Aviation - 8th ASE Conf., Jun 2016

PSL Parameter Space

Airflow Conditions

- (Duct Geometry)
- Pressure Altitude, P_0
- Mach, Air Mass Flow Rate, W_a
- Temperature, T_{PL}
- Relative Humidity, RH_{PL}

PSL is Isentropic & Adiabatic

Physics of the Process:

- Liquid water issues from the spraybars.
- Water particles immediately start to evaporate.
- Particles start to chill/freezing as they travel through the plenum and into the contraction.
- The vapor ...

Spray Conditions

- Nozzle Type & #: Mod1, Std
- Water Pressure, P_{wat}
- Air Pressure, P_{air}
- Air/Water Temp, T_{air} , T_{wat}
- Water Source: City, DI
- Spraybar Cooling Air and Pressure

Setting Conditions

Customer Provides

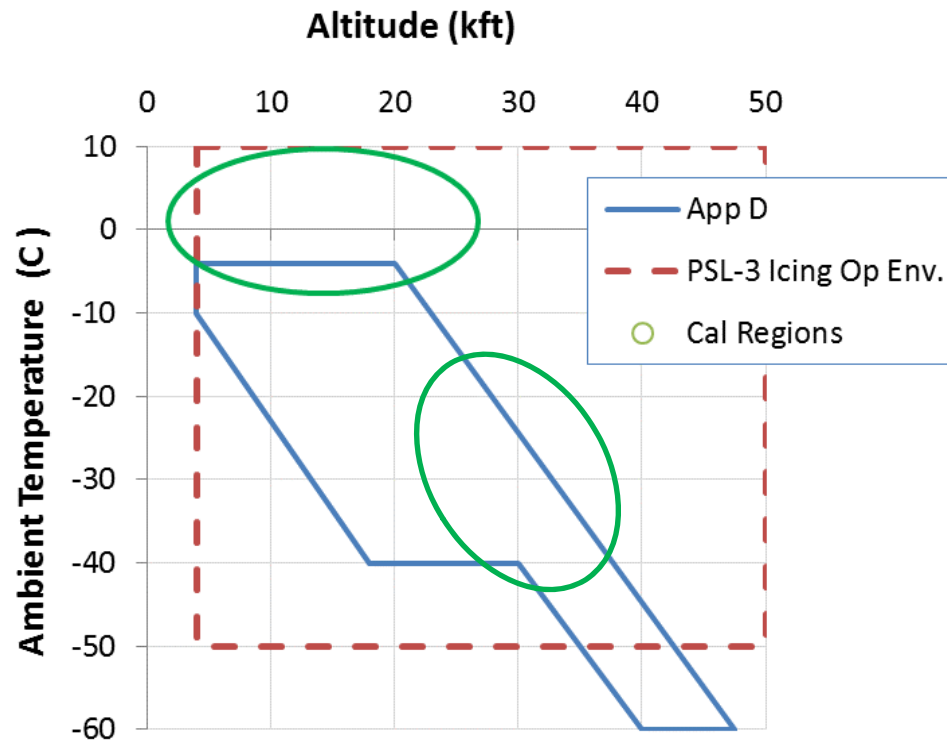
Ranges at Plane of Interest
(inlet to Fan or Booster):

- P_s , static pressure
- T_s , static temperature
- Mach
- Altitude
- TWC, Total Water Content
- MVD (Particle Size)

NASA Actions

- Calculate W_a to set Facility Conditions
- Characterize Spray Conditions
- Phase of particles at Sta 1 primarily a function of wet bulb Temp, T_{wb} . New model to predict (T. Bartkus).

PSL Cloud Characterization Envelops



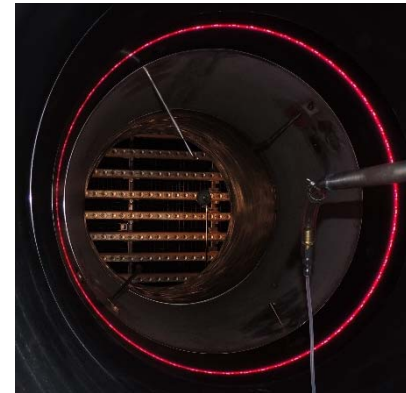
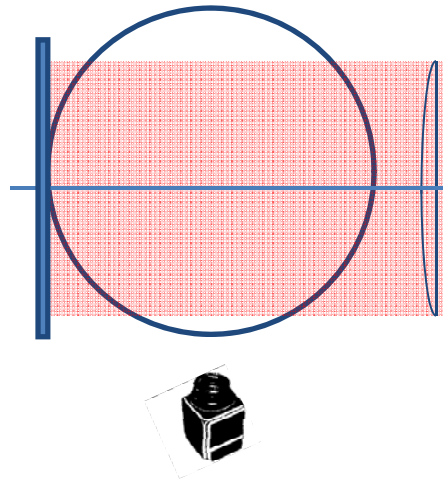
Two regions of conditions simulated

- Engine Fan Face (Honeywell Engine Tests LF01 & LF11)
- Aft of Fan / Inside Booster (Fundamental Ice Crystal Icing Study, Struk et. al)

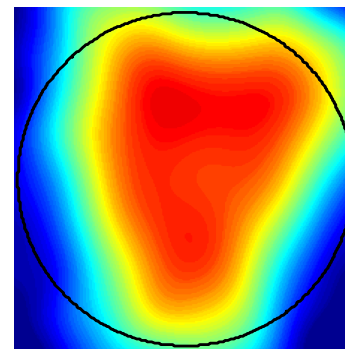
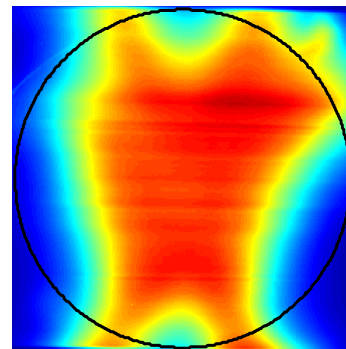
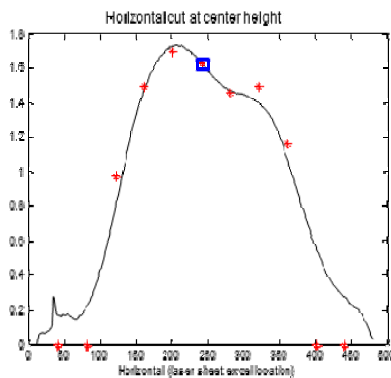
PSL Cloud Characterization Process

- Cloud Uniformity
- Total Water Content
 - Measurements in Center
 - Bulk average in Cross-Section
- Particle Size
- Particle Phase and Temperature - *T. Bencic will cover next talk.*

Cloud Uniformity



AIAA's
2014 Van Zante &
2015 Bencic et.al:
Good agreement
between these
three methods.



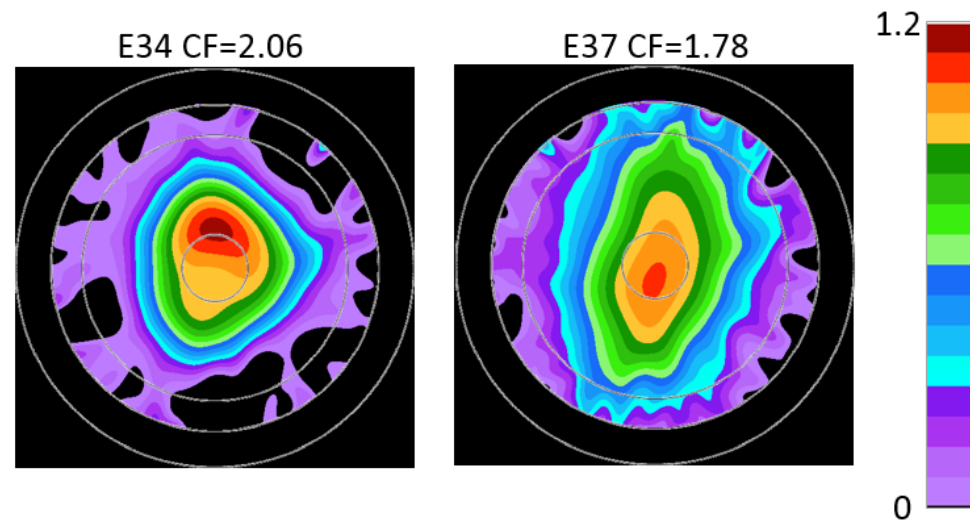
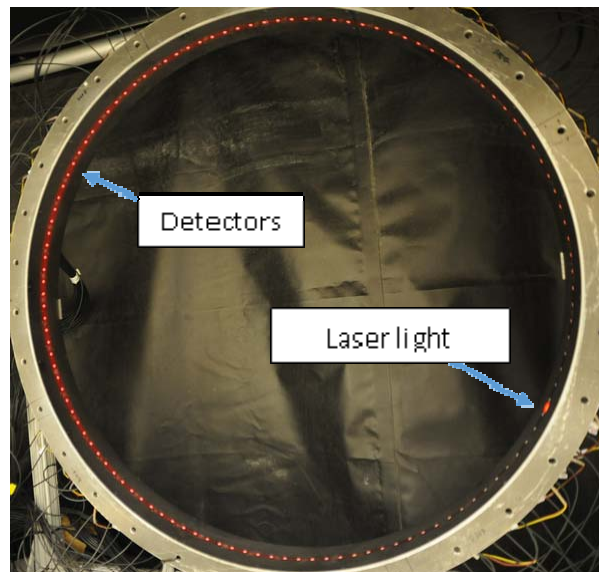
Tomography is
the diagnostic of
choice.

Grid

Laser Sheet

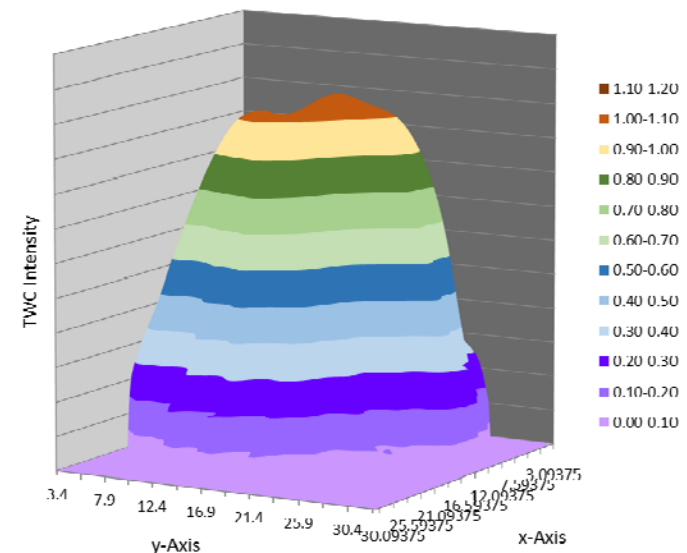
Tomography

Tomography – near real-time monitoring



Procedure:

- Measure light extinction with cloud OFF (baseline)
- Measure light extinction with cloud ON
(extinction due to size and number of particles)
- Intensity Ratio, I_{ij} , output at every 'pixel' (i, j)
- Calculate avg Intensity Ratio over 1x1-in Center, I_{00}
- Calculate Concentration Factor, CF, $I_{00}/\sum I_{ij}$



Total Water Content: Measurements

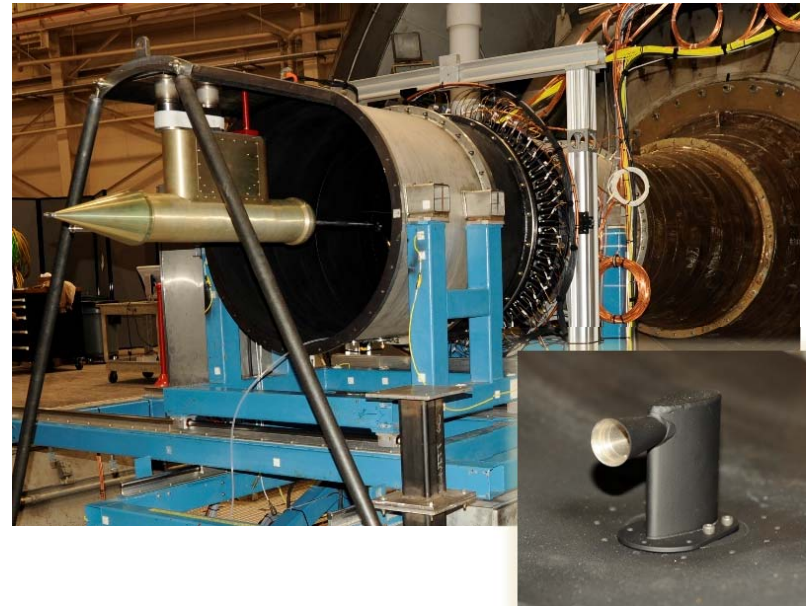
SEA, Inc.



Multi-Wire
(MW)



Robust Probe
(RP)



Iso-Kinetic Probe
(IKP2)

All measurements at Duct Center, TWC_{00}

MW and RP Notes

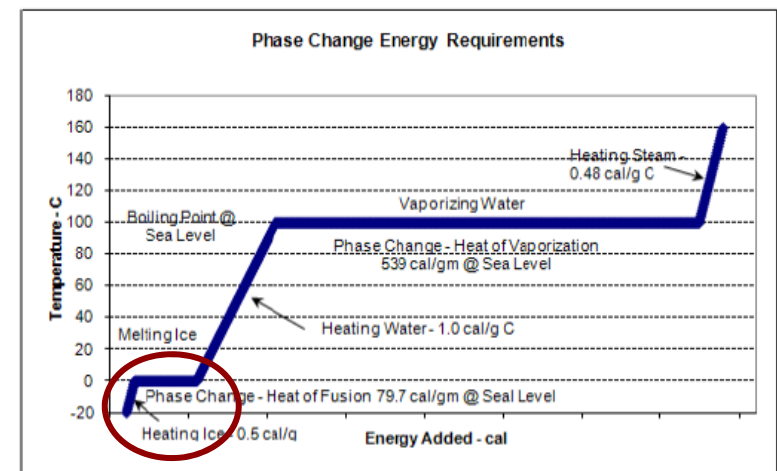
- Meas. power to evap. impinging water
- Minimize flow angularity into MW head
- Correct for Collection (Collision) Efficiency, MW only. Effects of particle bouncing, splashing not accounted for.
- Track default TWC (100% liquid)
- Added iWC (100% ice crystal)



$$TWC = \frac{K * P_{wet}}{[C_{liq}(T_{evap} - T_{amb}) + L_{evap}] * VTAS * L * W}$$

$$iWC = \frac{K * P_{wet}}{[C_{ice}(T_0 - T_{amb}) + L_{fus} + C_{liq}(T_{evap} - T_{amb}) + L_{evap}] * VTAS * L * W}$$

- iWC / TWC ~ 0.88

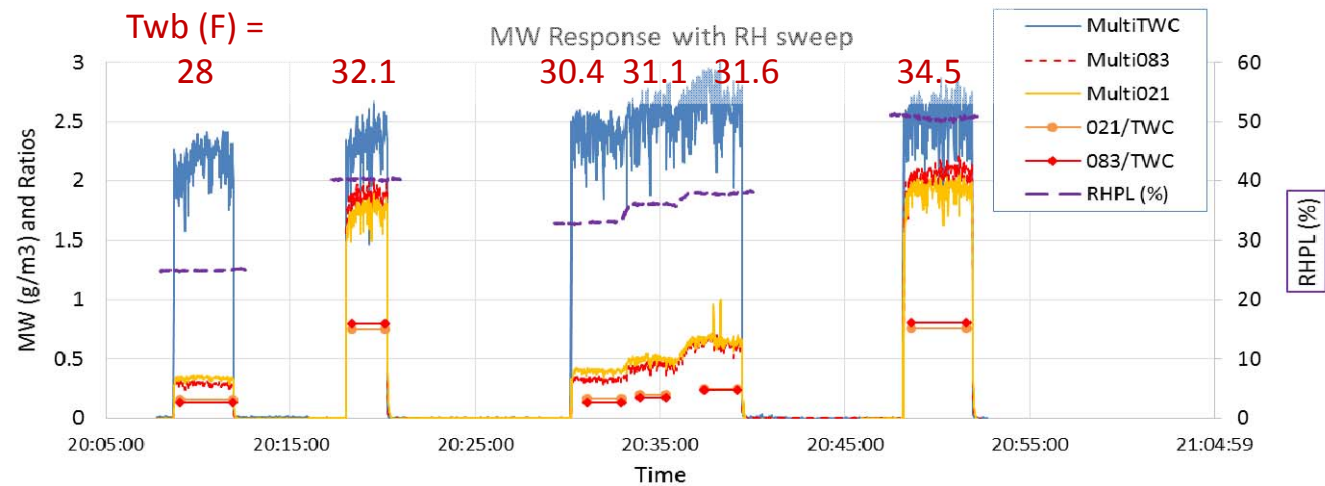


SEA, Inc. WCM-2000 User's Manual

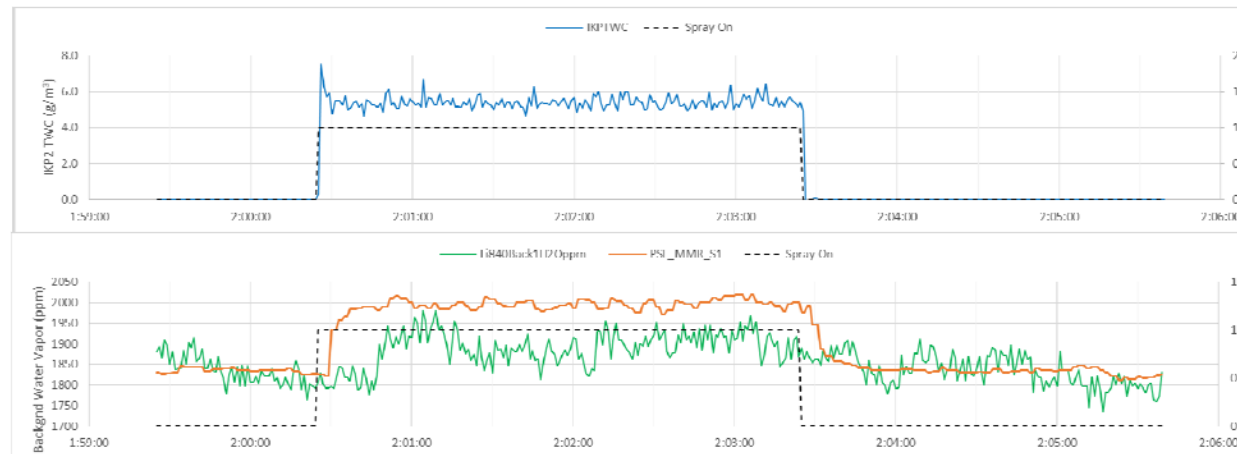
IKP Notes

- Iso-kinetically ingests air and cloud particles (no gain or loss of mass)
- Evaporates all cloud particles, regardless of phase; measures total water vapor
- Independent measure of background water vapor is subtracted so that only Ice + Liquid phases are calculated.
- At PSL, several sources of water vapor measurements at Sta 1. Largest correction applied.
- At PSL, a radial profile of water vapor was observed (Fundamental Ice Crystal Icing Study, P. Struk, 3/2016)

Sample TWC time traces



MW
RHPL Sweep
& Melt Ratio



IKP2
RHS1

Total Water Content: Bulk_Water Flow

Simple Calculation based on injected Water Flow Rate, W_f , Air Mass Flow Rate, W_a , and Sta 1 statics. Constant C includes density of water. Assume uniform distribution across Sta 1 Duct.

$$W_f \text{ (gal/min)} = \#Noz * C_{fn} * \sqrt{(\Delta P)}$$

$$TWC_Wf \text{ (g/m}^3\text{)} = C * W_f * P_{s1} / (W_a * T_{s1})$$

If add a cloud Displacement or Boundary Layer thickness δ

$$TWC_Wf_BL \text{ (g/m}^3\text{)} = C * W_f * P_{s1} / (W_a * ((R-\delta)/R))^2 * T_{s1})$$

TWC_Wf is the *basis function* for TWC measurements

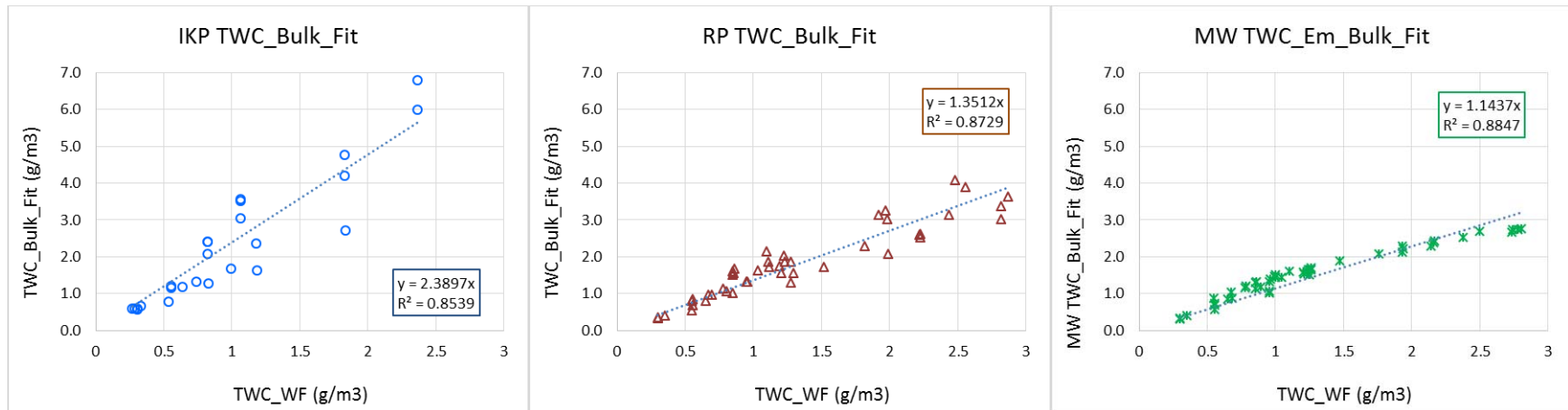
TWC_Wf_BL was recommended for LF01 and LF11 Tests

Total Water Content: Bulk_Meas

- Combine Measured TWC_{00} and Tomography CF.

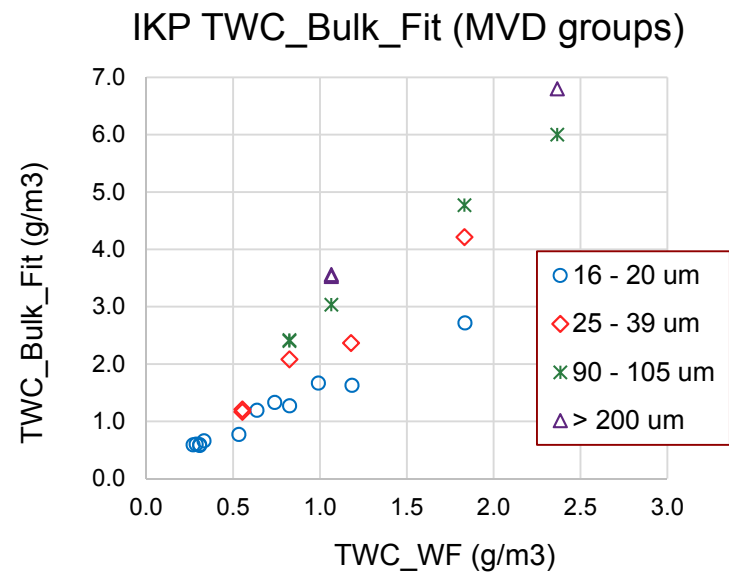
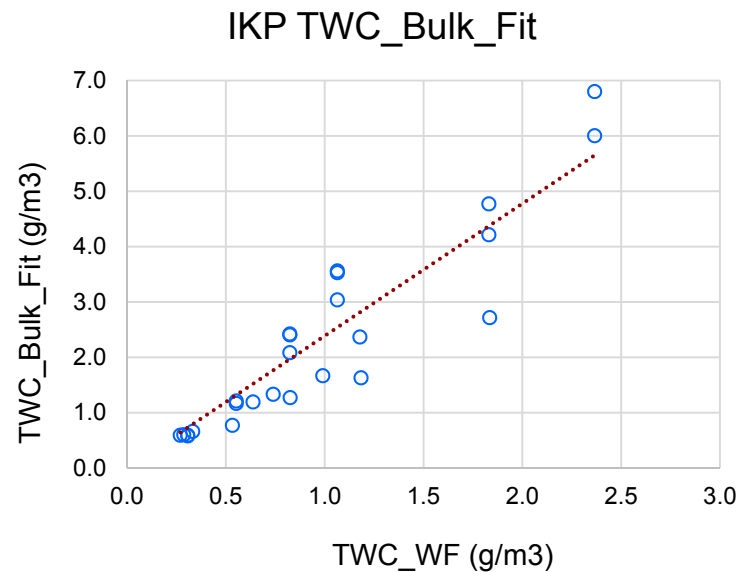
$$TWC_Bulk_Meas \text{ (g/m}^3\text{)} = \sum (I_{ij} * (TWC_{00}/I_{00}) * A_{ij}) / \sum A_{ij}$$

- Created a CF curve fit based upon Pair and TWC_Wf , TWC_Bulk_Fit



TWC & radial distribution of particle size

- Scatter in data due to radial MVD effect. CFD predicts larger particles concentrated at center, while smaller particles more uniformly distributed.
- This radial MVD profile is *not* currently incorporated into the tomography intensity ratios.



TWC Bulk Comparison

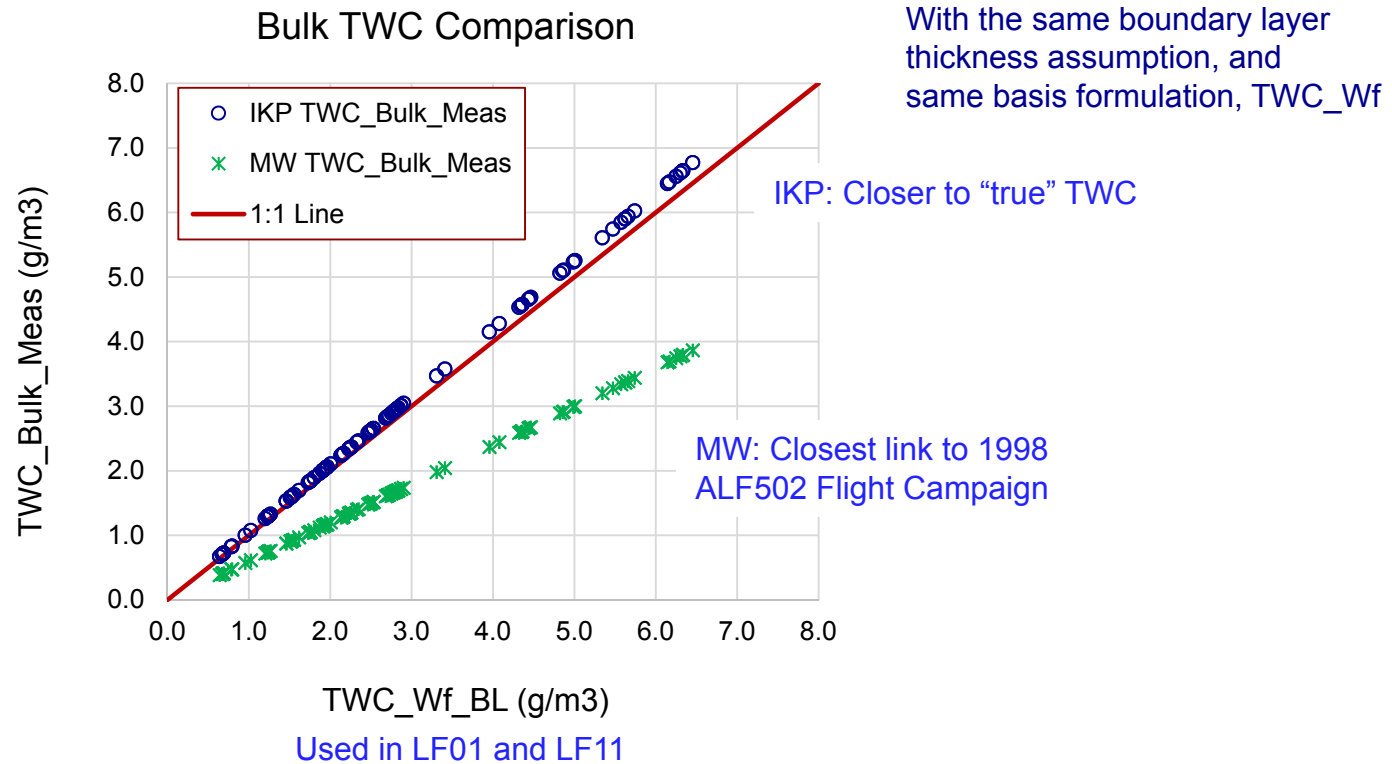
IKP + Tomography \approx Water Flow + Boundary Layer

Bulk TWC

TWC_Bulk_Meas

Bulk TWC

TWC_Wf_BL



Particle Size: Measurements

DMT, Inc.



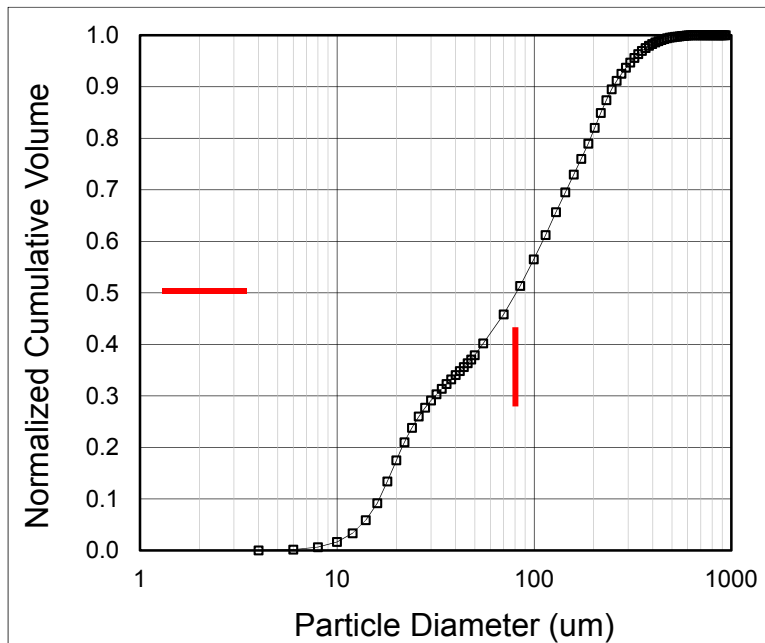
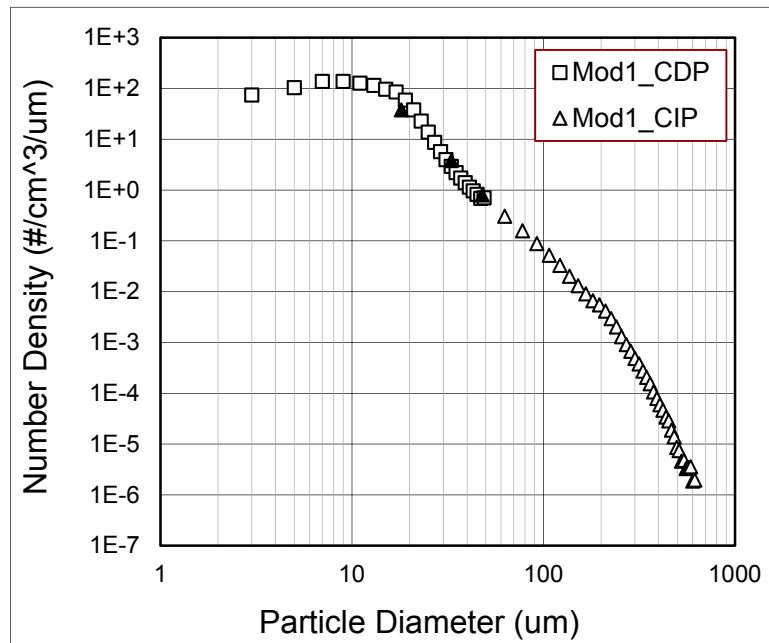
Cloud Droplet Probe
(CDP)
Refracted + Diffracted Light



Cloud Imaging Probe
(CIP-GS)
Shadowing

All measurements at Duct Center.
Future ability to shift off-center

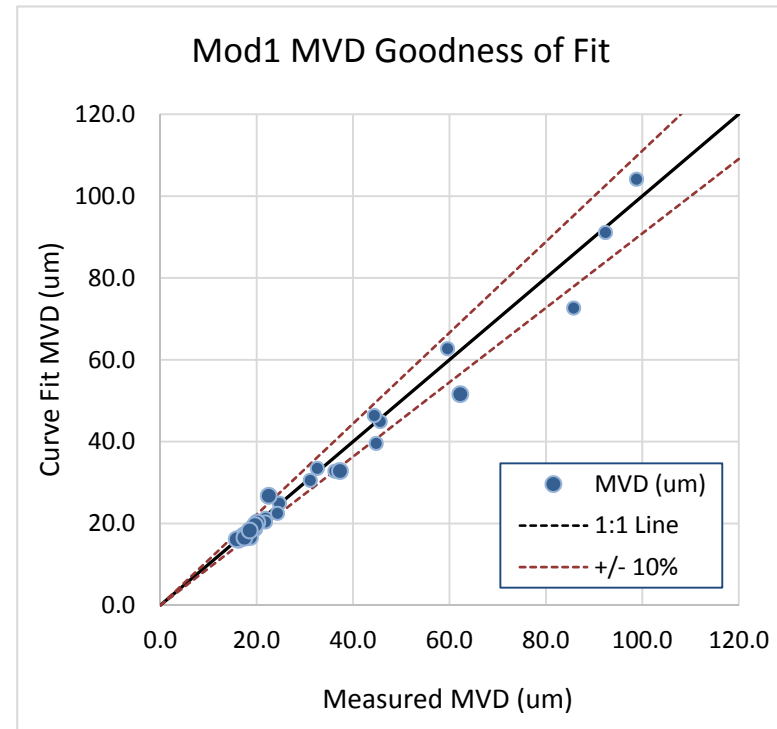
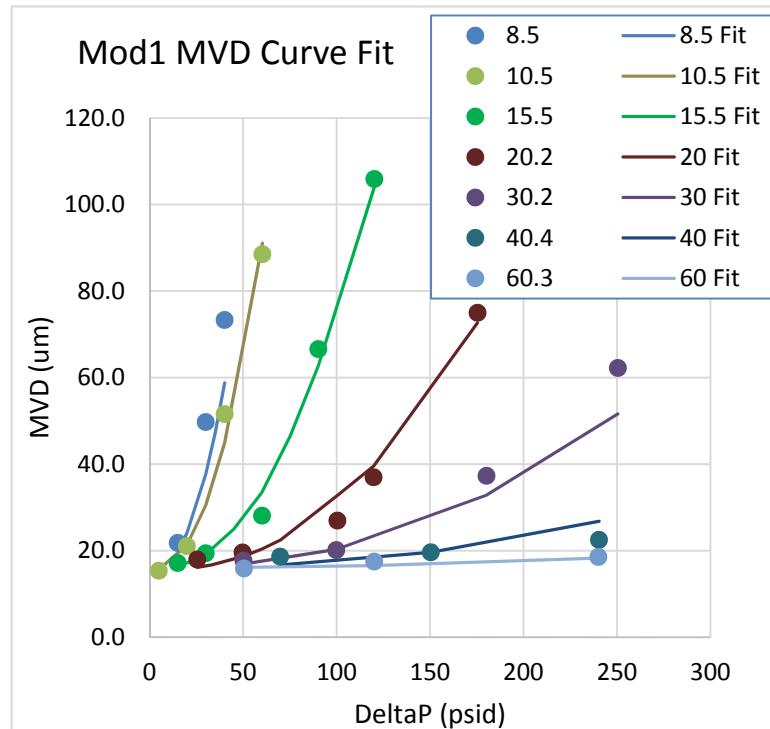
CDP + CIP Particle Size Distributions



Sample PSD: For the **CDP** survey, **Tair, Twat & TPL** were 'warm'.
For the **CIP** survey, **Tair, Twat & TPL** were at test conditions, 'cold'.
Same Alt, Mach and RHPL.

Pair = 20 psid, DeltaP = 175 psid; MVD = 80 μm

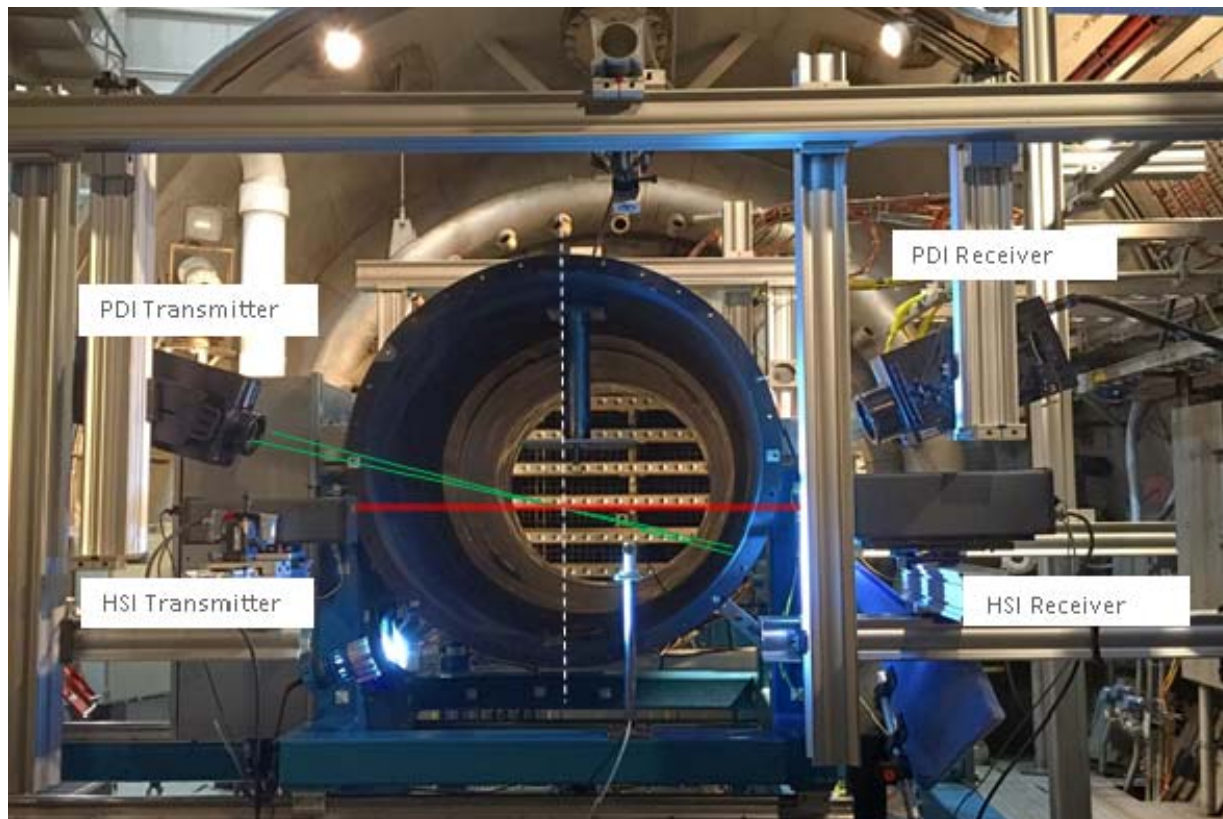
Mod-1 MVD Curve Fit



For LF11 MVD sweeps: Given a Pair line, increase DeltaP. This “guarantees” an increase in MVD, even if exact values are not known.

Additional PSD Measurements

Artium, Inc.



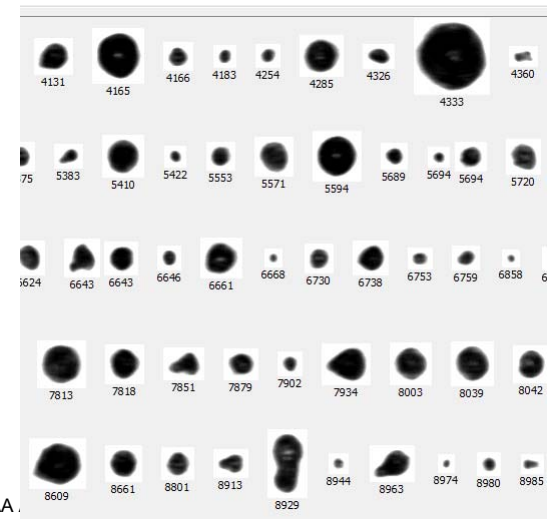
Both PDI and HSI are non-intrusive.
Have taken data in two most recent efforts
at center and off-center. Will be reported in future.

Phase Doppler Interferometer PDI

- Particle size (liquid only)
- Particle velocity
- Number density
- LWC

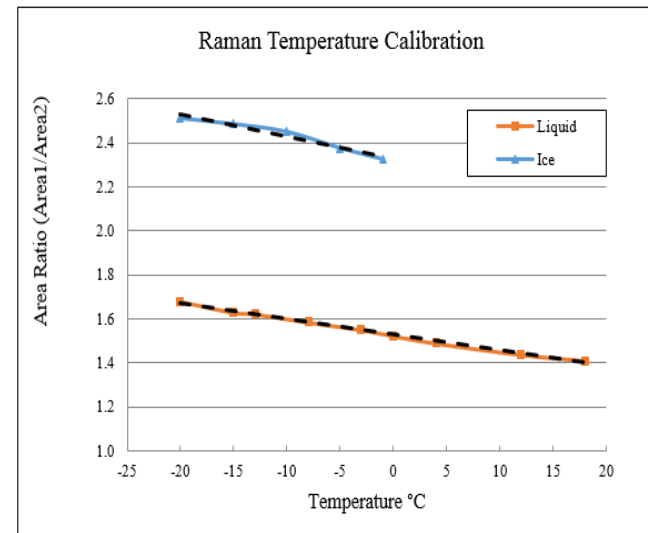
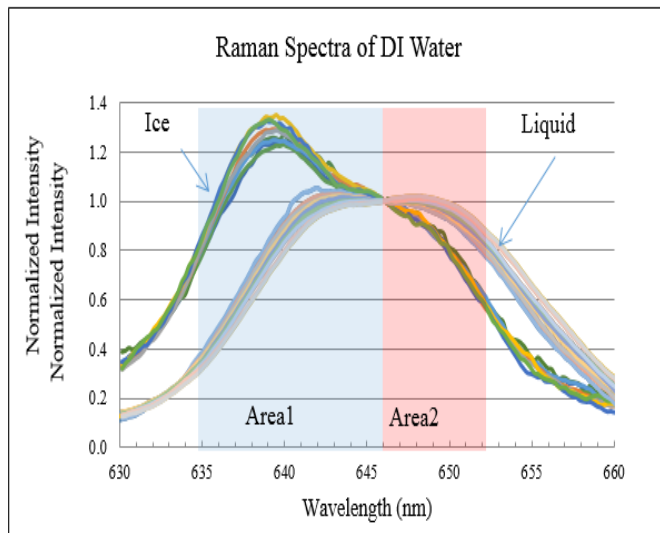
High Speed Imager HSI

- Particle size (ice & liquid)
- Shape
- Number density
- TWC



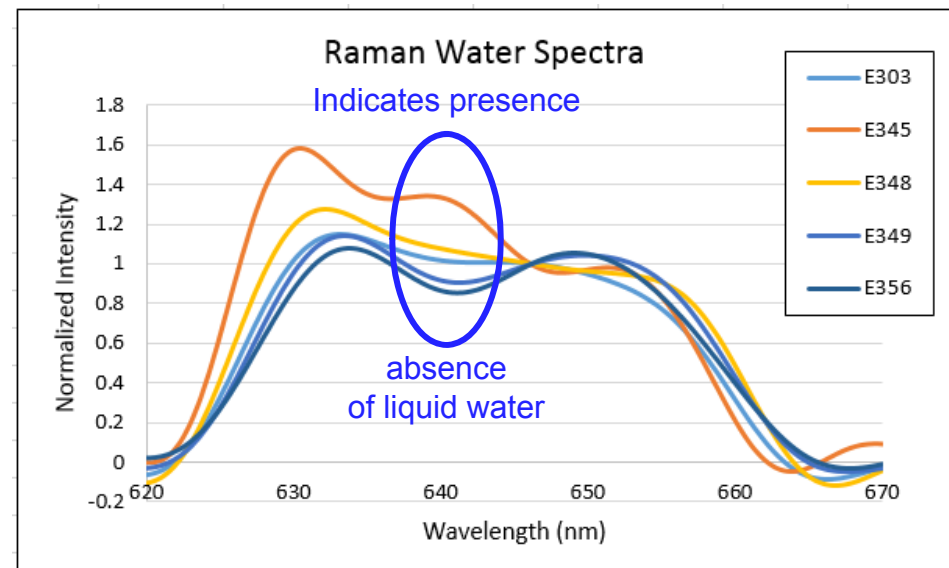
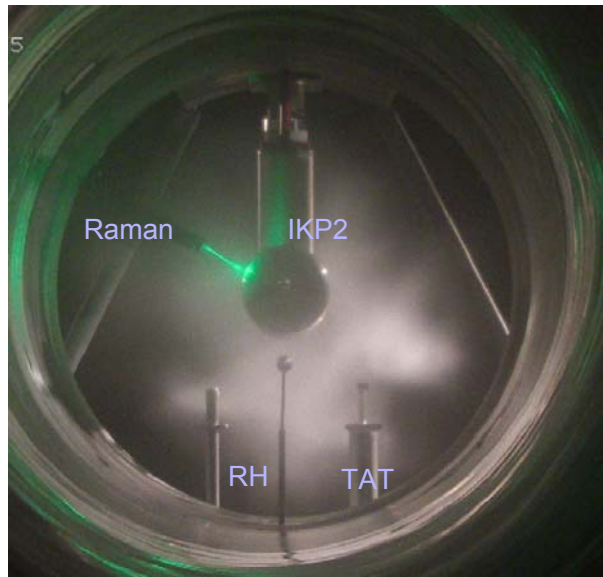
Particle Phase and Temperature

- Raman Spectra can evaluate bonded structure of water in both liquid and solid phases, as well as temperature.
- Benchtop success



Particle Phase, Temperature - Raman

- “Point” measurement at beam waist
- Some success in PSL, with particles moving at 0.5 Mach
- Continuing development



Conclusions

- Cloud Cal Space is 12-parameters with complex interactions
- Radial variations (concentrations in center) noted in
 - TWC, total water content
 - PSD, particle size distribution
 - RH, relative humidity
- Near-independent verification of Bulk TWC measurement: IKP2 + Tomography within 5% of Water Flow with Boundary Layer
- Lowest confidence measurement is ice crystal PSD, MVD. Actively investigating alternate methods.
- Some success with measuring Particle Phase, Temp. via Raman Spectroscopy

